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A Survey of Solid-State Microwave Power Devices

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MASSACHUSETTS INSTITUTE OF TECHNOLOGY

LEXINGTON, MASSACHUSETTS

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This technical report has been reviewed and is approved for publication.

FOR THE COMMANDER

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A SURVEY OF SOLID-STATE MICROWAVE POWER DEVICES

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ABSTRACT

Current capabilities of solid-state microwave power devices useful for CW power amplification in satellite communication systems are described. Devices discussed in detail include IMPATT diodes, bipolar and field-effect transistors. Also discussed are transferred electron diodes and TRAPATT diodes. Topics considered include physical device description, circuit design and performance, reliability, applications, and future trends.

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I. INTRODUCTION

Communication by satellite is playing an increasing role in information transfer for the scientific, domestic, and military communities. One of the variables determining the scope of present and future satellite communication systems is the hardware capability of the RF technology. This report discusses a specific part of that technology, RF power semiconductor devices. Advances in this area suggest the continuing possibility of physically smaller and lighter transmitters of increased power output and lifetime. Although the evolution of these devices has been hastened by development programs not related to communications (high-power pulse radars and ECM techniques, for example), the discussion here will be limited to those units which are useful as sources (or amplifiers) of CW power in the frequency range above 200 MHz. IMPATT diodes, bipolar and field-effect transistors will be discussed in detail, and TRAPATT and transferred-electron diodes will be mentioned briefly. Specific topics for the three units of interest include physical device description, circuit design considerations, reliability, applications, performance (output power and efficiency), and a look at future trends.

II. IMPATT DIODES

An IMPATT diode exhibits negative resistance at microwave frequencies and can thus be used to generate or amplify RF power. The frequency at which the device is useful can be as low as 1-2 GHz, and as high as several hundred gigahertz, with the RF power levels and DC to RF conversion efficiency high enough to be useful for many applications. Since the physical processes accounting for negative resistance are inherently noisy, IMPATT diodes are generally most useful operating at maximum saturated output power well above output noise levels.

A. Device Description

The negative resistance properties of an IMPATT diode arise from a combination of a) carrier generation by impact ionization and b) transit

time effects. Essentially, such a device is a p-n junction or Schottky barrier diode, biased in the avalanche region of its I-V characteristics, with a doping profile that provides the desired combination of carrier generation and transit time delay to allow terminal current to lag terminal voltage by more than 90°. Because of the periodic nature of transit-time effects, there is a limited negative resistance bandwidth, depending on the device profile. The frequency at which negative resistance begins to occur is often called the "avalanche frequency" f_a, and for a given diode, f_a is proportional to bias current, often as theoretically predicted, i.e.,

$$f_a = k\sqrt{I_{DC}} \ .$$

Thus the frequencies at which the device is useful, as well as the RF power and generation efficiency available, are all dependent on doping profile, device geometry, and bias conditions. The device outline for a 40 GHz silicon p-n junction flat profile device is shown in Fig. 1. The choice of profile for an application is determined by several considerations. Among these are reliability aspects, circuit considerations, operating frequency, and noise performance.

B. Circuit Considerations

Usually the desired goal of the circuit designer is to obtain the maximum RF power from the IMPATT for any given DC input power. There are several problems that are common to all IMPATT diodes which must be carefully considered during circuit design. First, the impedance levels of IMPATT diodes are low, i.e., maybe a few ohms of negative resistance with a negative Q of usually not less than 3-4. What this means is that low-loss impedance transformations are required and these can be complicated when a broad bandwidth amplifier is required. With high-Q cavity oscillators, there can often be a sizable power loss in the cavity itself.

Second, there is the stability problem. Since the inherent negative resistance bandwidth can be quite large (> an octave), stable networks for

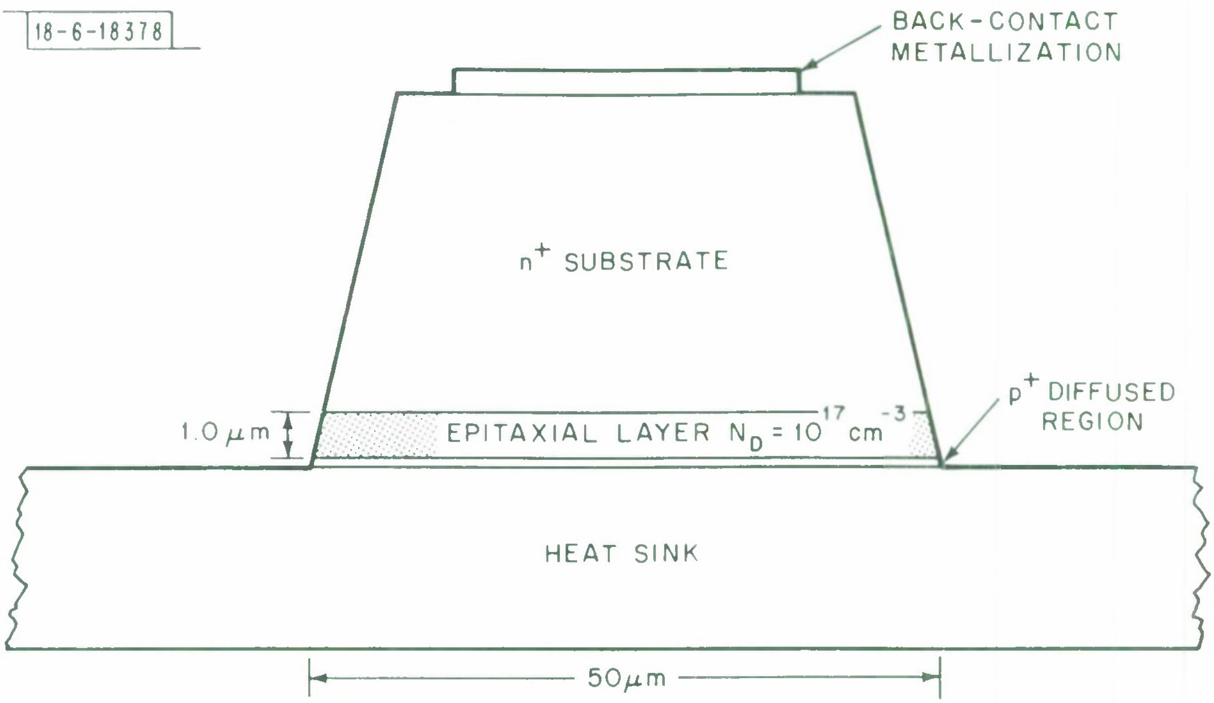

Fig.1. Device structure (cross-sectional view) of silicon single-drift IMPATT diode. Dimensions and doping densities are typical of devices designed for 40 GHz operation.

broadband amplifiers are often difficult to achieve. Further, since IMPATT diodes are characterized by a nonlinear inductive reactance, parametric instabilities readily occur under large signal drive.[1] These instabilities limit the RF power capability severely and their elimination requires tight circuit control from very low frequencies to generally at least the operating frequency.[2]

Other circuit considerations include harmonic tuning for enhanced fundamental performance, DC bias circuit design for burn-out protection, and package design reliability and ruggedness.

Circuit aspects and limitations will be discussed for the various profiles considered.

C. Flat Profile Devices

Flat profile devices are characterized by fabrication simplicity, demonstrated reliability, and well-defined design procedures.

1. GaAs Devices

GaAs p-n junction devices at present have 10-12 percent conversion efficiency with RF power levels of 2-3 watts at 10 GHz[3] and 1/2 watt at 40 GHz[4]. Schottky barrier devices have had better efficiency ($\approx$ 15 percent) and a little more power but suffered early reliability problems[5]. Although solutions to these problems have been proposed[6], Schottky barrier IMPATTs have not yet been embraced by the manufacturing community.

Properly designed GaAs p-n junction units normally operate with a small signal negative resistance of 5-10 ohms with a negative Q of about 3. The negative resistance drops by a factor of two or more under fully driven conditions when the peak RF voltage across the device is about half the breakdown voltage[7]. Parametric stability is difficult to achieve with these devices and subharmonic generation readily occurs. The cure is typically a low inductance termination at the subharmonic, of reactance value about half the reactance of the breakdown capacitance.[8] The self-rectification properties of these devices is fairly severe, i.e., the dc voltage may decrease by 20% of its value under cold RF conditions. This constrains the current regulation bias supply to respond to the onset of RF well within the thermal time

constant of the diode (a microsecond or less) in order to prevent tuning induced failures.

2. Silicon Devices

At frequencies less than 40 GHz, silicon single-drift devices are generally less efficient than GaAs, being about 10% maximum and more often 6-8 percent. The RF power levels are likewise about half of that available from GaAs. The power saturates when the peak RF voltage is about a third of the breakdown voltage. Parametric instabilities are less common than with GaAs and the voltage drop-back or self-rectification properties are less. Tuning-induced failures are much less common in silicon devices. All of these reasons make circuit design with silicon devices easier than with GaAs devices.

D. Double-Drift Devices

Double-drift devices have a drift region on both sides of the junction, one for holes and the other for electrons. The structure is roughly equivalent to a series-connected pair of single-drift devices, and the resultant increase in impedance level relative to a single-drift unit is advantageous to the circuit designer. Impedance transformations are generally less severe and parametric stability is relatively easily achieved. Results showing that double-drift devices have higher efficiency (and therefore higher RF burn-out power, or equivalently, lower operating temperature for a given output power level), and lower current density than single-drift units, are consistent with this simple model[9].

Most double-drift devices are presently silicon and these span the frequency range from X-band to 100 GHz. Double-drift CW results are 3-4 watts at X-band (commercially available),[10] 1.5 watts at 50 GHz[11] and 700 mW at 94 GHz[12]. Some effort has begun to make GaAs double-drift IMPATTs in order to take advantage of lower operating voltage and higher efficiency. Predictions of 25 watts pulsed at 10 GHz at duty cycles near 20% are based on present results of 10 watts pulsed.

E. Hi-Lo and Lo-Hi-Lo Profiles

GaAs modified profile units have produced efficiencies and RF power levels typically a factor of two higher than are available from the single-drift flat-profile technology. The lo-hi-lo or hi-lo doping profile results in a classical Read internal electric field distribution. The best results have usually been obtained with Schottky barrier devices, which typically give 20-25 percent conversion efficiency at 3-5 watts for a single diode from C-band to K_u-band. 37% at 3.4W has been reported at 3 GHz[13]. Power levels of 8-10 watts at conservative operating levels ($T_J \approx 220°C$) have been achieved in multiple mesa geometries at X-band[3].

Indications are that modified profile devices are generally more difficult to control in a circuit environment than flat-profile devices. Low impedance levels under fully driven, maximum efficiency conditions can make low gain a requirement for stability and magnify the effect of circuit losses. High gain amplifiers are generally unstable in the absence of large RF signal inputs, requiring bias to be applied synchronous with RF inputs. Parametric instabilities seem to be less severe in these devices, possibly because of depletion region width modulation. Second harmonic tuning at these large signals will probably be significant. Large self-rectification in these diodes results in large (10-20%) drops in DC voltage at full RF output and complicates design of bias current regulators.

These devices are a new perturbation on IMPATT technology and there is much to learn about circuit design, device fabrication, and reliability.

F. RF Performance 1977

Performance results which typify IMPATT device capability are shown in Fig. 2. CW oscillator power as a function of frequency is plotted, with DC-to-RF conversion efficiency noted. References are given in parentheses. Advances in epitaxial growth and ion-implanation techniques account for the appearance of modified profile devices at the frequencies less than 10 GHz. Attempts to extend these successes to higher frequencies are under way.

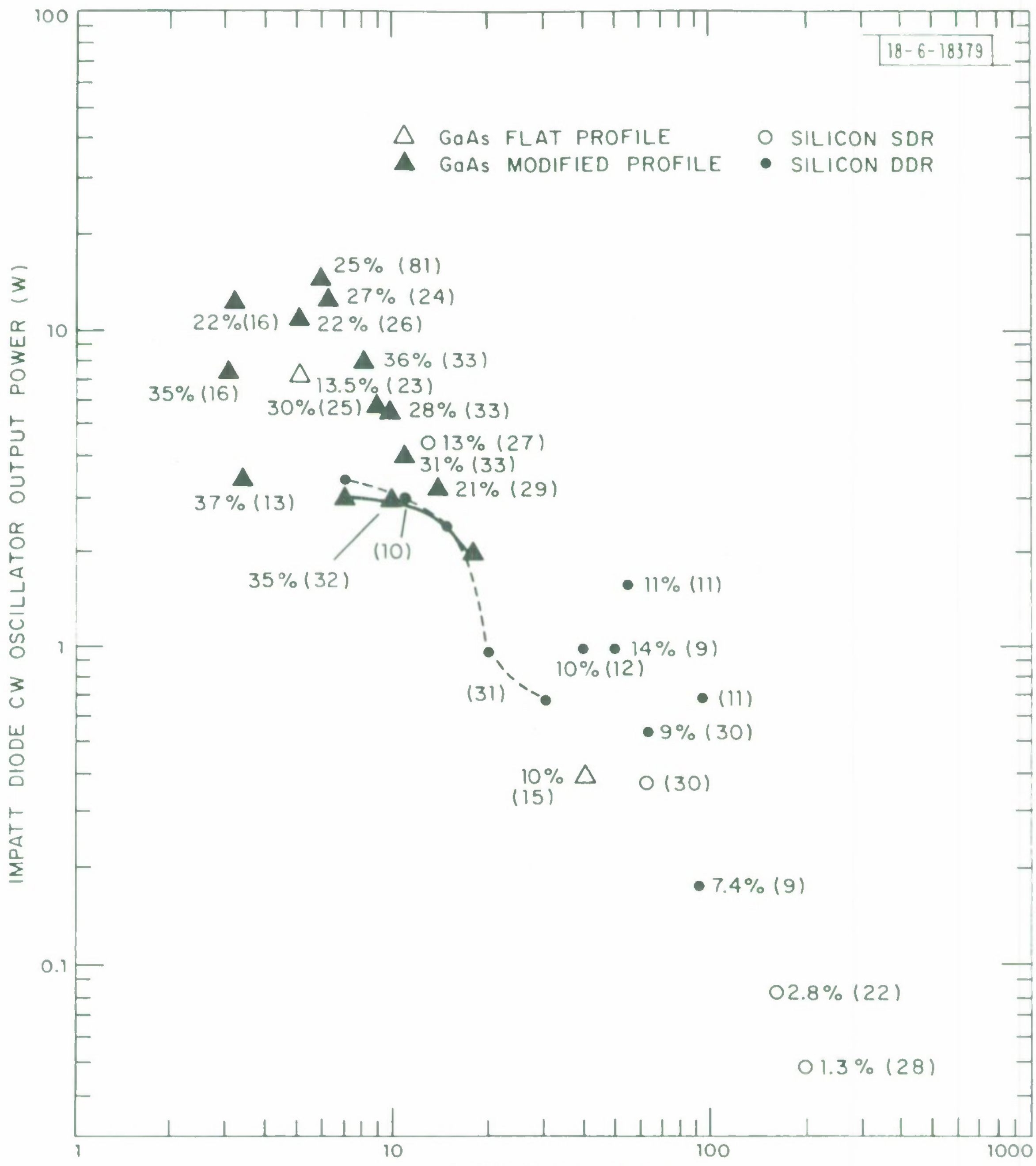

Fig.2. IMPATT diode performance (CW oscillator output power vs frequency) Data points represent laboratory results or commercially available devices. DC-to-RF conversion efficiency and references are noted for each point.

G. Reliability

Because of the high DC power density in the IMPATT, junction temperature appears to be the dominant cause of intrinsic failures, at least for lower efficiency devices. Early designs of device geometry, therefore, concentrated on minimizing the distance between the junction and heat sink. Schottky barrier devices were ideal in this regard because only the barrier metal and a bonding layer separated the heat generator volume from the heat sink. Unfortunately, in the case of GaAs devices, the platinum barrier metal was shown to be time and temperature unstable,[5] reacting to form a PtAs alloy, which degraded the electrical and thermal characteristics of the device. The results of continuing research at Bell Laboratories[6] report that a tungsten barrier layer is effective in stabilizing the Schottky barrier movement.

With a diamond heat sink, the GaAs Schottky barrier IMPATT represents recent advances made in reliability and performance of single-drift structures. It should be noted that diamond is no longer a laboratory curiosity, being used commercially by at least two vendors. Because its thermal conductivity (κ_D) drops rapidly for operating temperatures of interest, however, its advantage over copper† decreases (at room temperature $\kappa_D/\kappa_{Cu} = 5$, and at 100C $\kappa_D/\kappa_{Cu} = 3$)[14]. Plated silver[15] as heat sink material has also been effectively used to replace early heat sink designs based on copper, but stresses the semiconductor material to the point of fracture if not properly processed. Finally, in an effort to reduce junction temperatures by altering geometry, annular structures have been proposed and fabricated.[16]

Because of the many varieties of IMPATT devices and the complexity and variation of the manufacturing process among laboratories and vendors, it is somewhat risky to assign universality to a failure mechanism discovered in a particular device manufactured by a particular vendor. Nevertheless, there is a fair amount of agreement on the physics and statistics of failure of

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† The thermal conductivity of copper (κ_{Cu}) is constant in this range.

IMPATT devices, at least for the single-drift structure, which has had the most test exposure. In addition to the problem with GaAs Pt-Schottky barrier devices, a penetration weakness of barrier metals separating the bonding metal (gold) from the active semiconductor has been cited as a cause of abrupt failure.[17, 18] Increases in the thickness of this barrier material have resulted in improved device lifetime[19] although the accompanying increase in thermal resistance does decrease the RF performance. A theoretical scenario involving time increases of leakage current with respect to avalanche current has also been proposed as a mechanism of abrupt failure,[20] but experimental results have not been published. Early reliability studies on Read-type GaAs structures based on high temperature storage have shown bimodal failure/time populations, suggesting two possible reliability problems.[21]

Statistics of IMPATT lifetime which have been published are summarized in Fig. 3. This figure shows MTTF data based on constant-stress, and elevated temperature storage tests. The plot is linear reciprocal absolute temperature vs. log time and thus represents the equation

$$\text{MTTF} \propto e^{E_a/kT}$$

(where k is Boltzmann's constant and T is absolute temperature) as a straight line with slope E_a. The circles are experimental data and the dashed lines represent extrapolation to lower junction temperature. At an operating temperature of 200°C, operating life of 10^6 - 10^8 hours is predicted. A sample of failure populations as a function of stress is shown in Fig. 4. The axes of this figure are arranged so that a straight line represents a fit to a log-normal distribution. Deviations from the linear behavior at early times are revealing indicators of problem devices. Efforts to trace these failures to the fabrication process or to "screen out" such devices for final accepted components are appropriate.

The reliability picture for single-drift IMPATT diodes, therefore, is fairly complete. Benchmark lifetime statistics and failure mechanisms exist

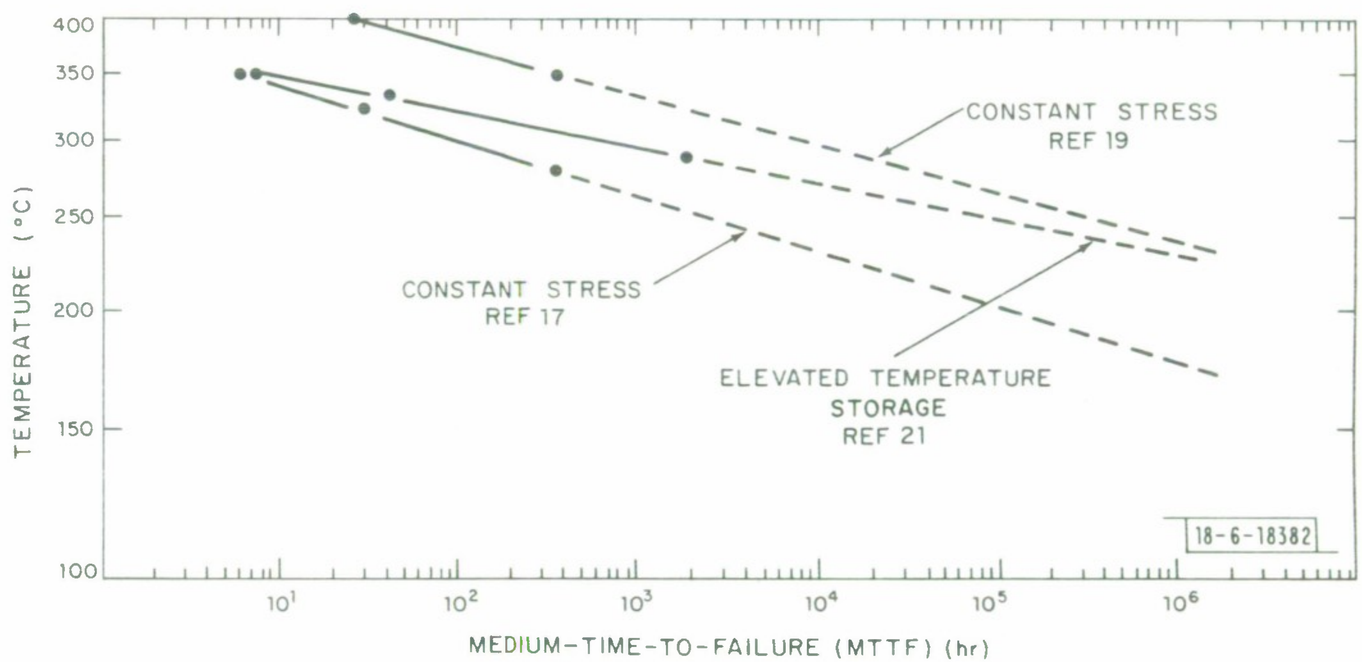

Fig.3. IMPATT diode reliability results. Data points show median times-to-failure of populations of devices at specific junction temperatures. Straight lines represent a fit to an Arrhenius rate equation (see text). Dashed lines show extensions to lower operating temperatures. References are noted.

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ERRATA SHEET
for
TECHNICAL NOTE 1977-14

The authors of Technical Note 1977-14 (P. W. Staecker and D. F. Peterson, "A Survey of Solid-State Microwave Power Devices," 29 April 1977) have discovered an error in Figure 3 (page 10). Abcissa values for median-time-to-failure (MTTF) (hr) are too low by a factor of 10. Thus 10^1 should read 10^2, and so forth. Please note this in your copy.

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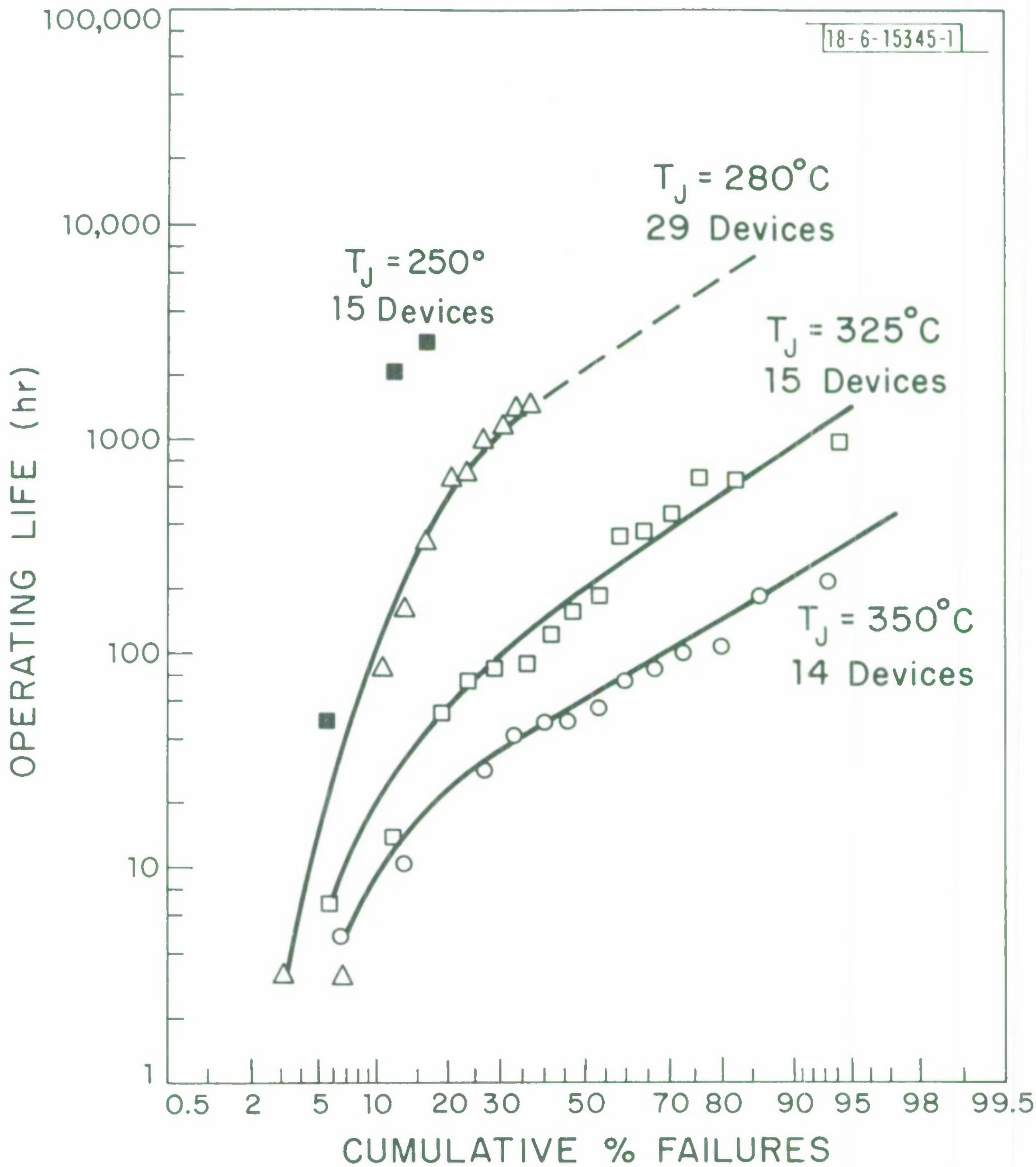

Fig.4. A family of IMPATT diode failure populations. (Ref.19)

which can be used to evaluate new members of the family. One should note, however, that a review and revision of these statistics and physics will become necessary as higher efficiency devices evolve. The Schottky barrier movement problem as applied to the operational life of high efficiency profile device, for example, would be expected to be much more severe since RF performance is highly dependent on the dimensions of the doped layers near the barrier. Future tests will necessarily stress the device in its intended RF environment (amplifier, oscillator, CW or pulse) to determine effects of higher RF energy densities on device lifetime.

H. Applications

The greatest application of IMPATT diodes is as power saturated RF oscillators and amplifiers. IMPATTs are presently the highest CW power solid-state device available, and they are fairly easy to power combine and control. Current R & D emphasis is being applied to develop IMPATTs as sources in the atmospheric passbands of 95, 140 and 200 GHz and the attenuation band near 60 GHz. Imbedded properly, these devices can be used effectively as amplifiers at maximum efficiency with controlled gain and input/output responses. High gain can be obtained in the injection locked oscillator mode or as a phase-locked amplifier, i.e., a voltage controlled IMPATT oscillator with a phase-locked loop around it. Since IMPATTs operating at maximum output levels are highly nonlinear, modulation is usually in the form of PM or FM.

Single-drift flat-profile GaAs devices presently are most widely used in CW applications, as they have reasonably good efficiency, high reliability, and can be manufactured consistently. These will likely be replaced with the high efficiency structures as the technology and circuit competence improves. These IMPATTs are presently used in short haul communications links, in instrumentation, and self-mixed doppler radar systems.

Double-drift devices are primarily used in high-power pulsed applications such as radar systems. By power combining many devices in a cavity, pulsed

power levels are well above 100 watts at X and K_u-band.

IMPATT diodes have poor noise properties, with typical device noise measures ranging from 30-50 dB. This limits their use as linear amplifiers, and restricts them to applications where noise is set by other system components or is not a problem.

I. Future

The single-drift low-efficiency IMPATT is well-understood from a circuit design point-of-view and has demonstrated reliability of some uniformity even over many various fabrication processes. This lifetime data is currently serving as the base line against which process changes are being measured. Double-drift diodes, the Read profile device, hybrids (double-drift Read), multiple device structures, and annular geometries represent the new methods of extending IMPATT potential. Double-drift structures seem to offer the easiest method of extending performance to high frequencies. Because of higher efficiencies of these devices, the question of reliability must be addressed again. A realistic goal for 1980 would be to demonstrate reliable operation of these devices at the power levels of Fig. 2, which are near or at burn-out levels.

III. BIPOLAR TRANSISTORS

The microwave bipolar transistor is historically the oldest solid state device capable of power amplification, and presently is the most sophisticated (or complicated) from design and fabrication viewpoints. Whereas its past success as a power device at microwave frequencies rests heavily on the perfection of the silicon technology developed for lower frequency units, its future growth seems limited by this material. Presently its useful range of operation extends from low frequencies to approximately 10 GHz, but microwave FETs (discussed below) afford most if not all of the advantages of bipolar power devices at frequencies above 4 GHz.

Several techniques have been utilized to achieve reliability of bipolar units. Temperature effects have been mitigated with high thermal conductivity substrates and multiple cell design. Emitter ballast resistors have been integrated into the emitter finger metallization, either in thin film form or as bulk diffused regions, to insure current sharing among base areas of a given cell. Internal matching to achieve better RF performance also has favorable reliability effects.

A. Device Description

A bipolar transistor consists of three regions: emitter, base, and collector. Transistor action is the dependence of majority carrier flow in the emitter and collector regions (output current) on the minority carrier flow in the base region (input current). When these carriers are electrons, the device is an n-p-n transistor. Figure 5 shows a cross sectional view of part of a transistor cell. The finger pattern is of interdigitated design.

Power capability of the device is affected by

a) the doping level and related thickness of the collector region, which, properly selected, can maximize the voltage and current tolerated by the device.

b) the emitter periphery (total perimeter of emitter metallization), which determines the current available at the emitter.

Frequency response and device ruggedness make conflicting demands on these and other parameters, requiring many design compromises in order to "optimize" the final device. High power handling capability requires a large collector breakdown voltage and hence a lightly doped collector region. High frequency operation requires short delay or transit times in all three regions of the vertical structure in Fig. 5. In the collector region this means heavy doping, in direct conflict with power handling requirements. A thin collector region will improve frequency response at the expense of decreased protection against changes in output VSWR.

Perhaps the most critical part of the horizontal geometry of the microwave bipolar transistor is the emitter periphery. A figure of merit commonly

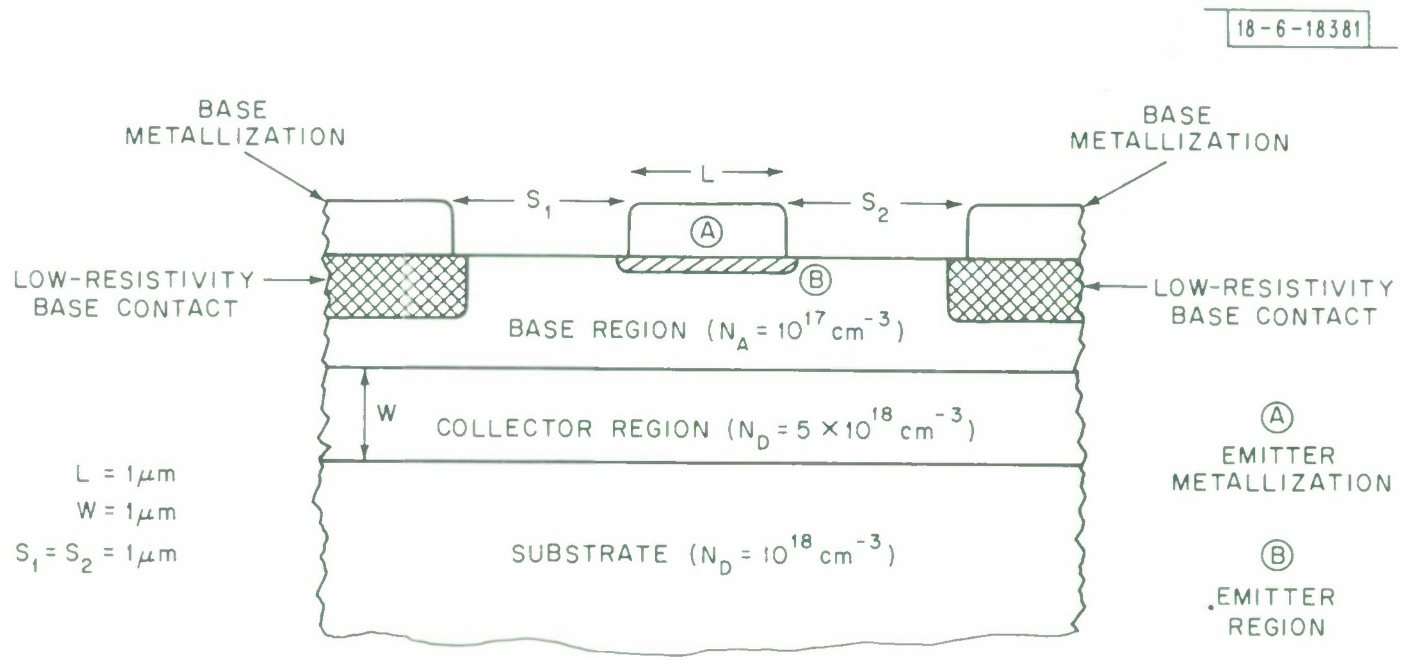

Fig.5. Device structure (cross-sectional view) of single-emitter silicon (n-p-n) bipolar transistor. Dimensions and doping densities are typical of a device designed for X-Band operation. (Ref.34) A "cell" is the array of repeated patterns of this structure, usually in interdigital fashion. Power devices use many cells connected in parallel.

used is the emitter-periphery-to-base-area ratio (aspect ratio), and various horizontal configurations have been invented to maximize this number.[35] Although increasing the aspect ratio will yield more watts at higher frequency (by decreasing the input resistance), it will also increase the power density and therefore temperature. A solution to this dilemma is to divide the active area into many smaller interconnected sites, but the associated parasitic reactances of the bonding pads and interconnects eventually limit this alternative. These considerations represent only some of the fabrication compromises involved in the making of this extremely complicated device.

B. Circuit Model

Circuit descriptions of bipolar transistors based on device physics allowing accurate characterization and optimization of small signal impedance levels, gain, and stability as functions of frequency are well-known.[36]

Power gain (G) is of particular importance to device designers and can be described by figures of merit related to the circuit model. In the microwave region, G decreases by 6 dB/octave, reaching unity at a frequency, f_{max}, the "maximum frequency of oscillation"

$$G = \left(\frac{f_{max}}{f}\right)^2$$

For a bipolar transistor, f_{max} depends on

a) the collector-base charging time constant $r_b' C_c$, where r_b' is the lumped equivalent base spreading resistance and C_c is an equivalent collector capacitance

b) The unity current gain frequency f_T, determined by the total transit time from emitter to collector.

f_{max} is a function of both horizontal and vertical structure, therefore, and is related to a) and b) by

$$f_{max} \approx \left(\frac{f_T}{8\pi r_b' C_c}\right)^{1/2}$$

Since $f_T \cong 10$ GHz is about the best achievable with current vertical technology, latest efforts to raise f_{max} have focussed on decreasing $r_b'C_c$. The 1μm horizontal geometry of Fig. 5 yields $r'_bC_c \sim 0.4$ psec and $f_{max} \sim 30$ GHz, adequate for X-band power operation.

The input impedance of the intrinsic transistor is small and real ($\sim 1\Omega$) and shows the effect of a forward-biased emitter-base junction. A small reactive part (j3) is caused mainly by lead inductance from the chip to the outside world. The output impedance is dominated by the collector-base capacitance. To consider and optimize inherently large signal effects such as saturated output power and efficiency, the above model in general does not apply. Large signal circuit models are largely empirically determined (for specific devices and frequency ranges), and because they are not well-understood physically, extrapolation to different devices or frequency ranges within the microwave region is difficult.

C. Circuit Design

Common-base configuration and Class C operation are commonly used to achieve large signal performance objectives at UHF and microwave frequencies. Circuit design at 1 GHz and higher still concentrates on multi-cell combining techniques to reduce parasitics and thus preserve power gain while increasing output power. At UHF, where these techniques are more straightforward, the emphasis shifts to thermal design of the package in order to maintain low junction temperatures for high power devices. Since microwave transistors operate in the f^{-2} portion of the power gain curve, input circuit design serves two purposes:

1. provide a transformation from low complex chip impedance to higher real levels.
2. provide reactive gain flattening over the frequency band of interest.

1) allows direct paralleling (and its advantages) of similar units whereas 2) sets the maximum power gain and determines its flatness. Input characteri-

zation can be implemented with large signal S-parameter techniques, and is fairly straightforward, provided low impedance levels are properly dealt with.

The output circuit design is of critical importance to saturated power, efficiency, and bandwidth. Techniques have been described for optimizing these parameters by appropriately designed output circuits.[37] The purpose of the output circuit is to detune the transistor reactance to obtain maximum efficiency over the band of interest while providing a value of real load impedance appropriate to power output requirements. Accurate characterization of the transistor output is essential to output circuit design, but large signal S-parameter techniques simply do not apply to Class C operation. An alternative load-pull technique has been developed which can accurately model transistor output even under large signal Class C conditions.[38-40]

Both input and output matching networks are most effective when extremely close to the transistor chip. A recent and significant innovation in microwave bipolar transistor fabrication, due to frequent fabricator/circuit designer interaction, has been the inclusion of these networks internal to the package.

D. <u>RF Performance - 1977</u>

Figure 6 shows the current performance of bipolar units (CW <u>added</u> power {in order to remove any ambiguity regarding power gain} vs. frequency) with power added efficiency and literature references noted. See also Fig. 9 for a comparison to FET performance. All results shown are for Class C operations.

E. <u>Reliability</u>

The microwave power transistor is a complicated <u>system</u> of emitter and base finger arrays, ballast resistors, chip capacitors, thin film inductors, and wire-bond interconnects, each of which is subject to its own favorite failure mechanism. Device geometry, metallization schemes to minimize electromigration-caused failures, and fabrication processes differ

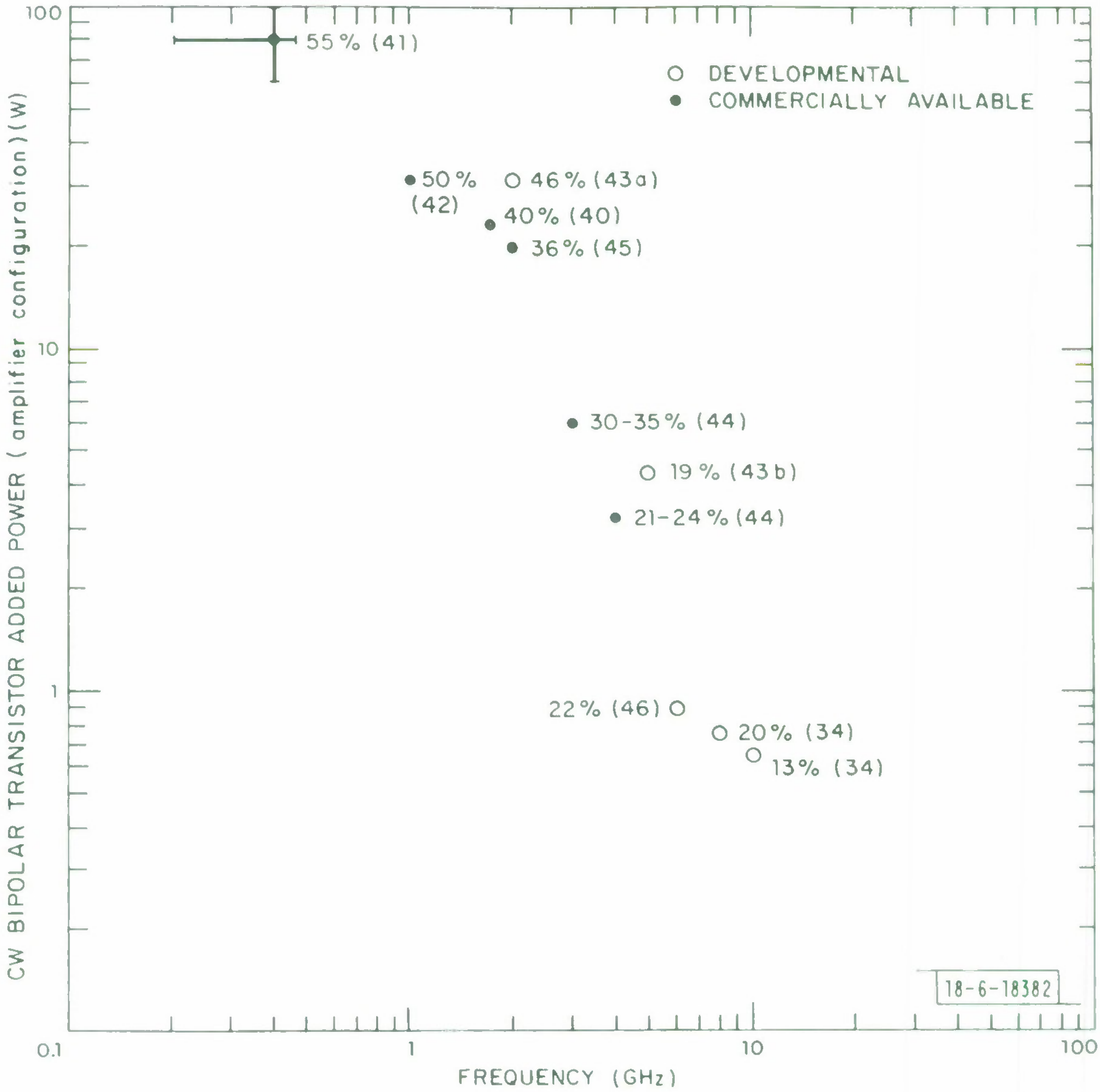

Fig.6. Bipolar transistor performance (CW amplifier added power vs frequency). Data points represent laboratory results or commercially available devices. Power added efficiency and references are noted for each point.

among manufacturers. We mention here the metallization controversy and the efforts of those who have studied lifetime statistics and have attempted to identify intrinsic failure mechanisms.

The most popular debate centers about the merits of aluminum versus gold-based systems as candidates for base and emitter finger metallization. Controversy persists because life test results are often misinterpreted.* Recently, however, progress in the direction of a definitive study[47] has been made between gold and aluminum metallizations on otherwise identical transistors processed by the same manufacturer. The conclusions are:

1. The gold-based system gives longer-lived devices than the aluminum system because the gold system is less prone to electromigration failure.
2. The aluminum-based system yields reliability figures that are adequate for present mission requirements. (This would be particularly true for a satellite application where mission life of 5 years usually applies).

In a recent study on gold 2 GHz units,[48] mode of operation has been examined. Results report a "tenuous" agreement between oscillator lifetime and dc operation based on comparison at two temperatures and qualitative arguments about current densities in oscillator operation. Amplifiers operating at the same two temperatures show much longer lifetimes, again consistent with arguments of lower effective duty cycle operation. Unfortunately, work on this project has been discontinued.[49]

Work by Poole and Walshak[50] on L-band aluminum devices dealt in detail with the effect of RF duty cycle and temperature upon device lifetime. Their results showed the median time-to-failure to vary inversely with pulse width and pulse duty factor.

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* A lifetime study of transistor A, a gold-based metallization process from one manufacturer and transistor B, an aluminum-based metallization process from a second manufacturer, is useful to the user who wants to know which device to choose. The results do not indicate the desirability of one metallization scheme over another, however, because many other process variables differ between manufacturers.

Such misinterpretations, it should be noted, are not limited to discussions of bipolar transistor metallization.

There appears to be fairly uniform agreement among manufacturers that the limiting wear-out mechanism for these devices is electromigration within the finger metallization, causing eventual voiding and performance degradation. The rate equation for electromigration is

$$MTTF = C\ J^{-n} \exp\ (E_a/kT)$$

where J is current density, n is a constant ($n \approx 2$), and C is a constant dependent on the grain structure of the film and other parameters.

Figure 7 summarizes recent published life statistics. These data show different devices and manufacturers, as well as a fairly broad spectrum of device environments, and indicate a remarkable agreement in activation energy among tests ($E_a \approx 1ev$).

Furthermore, applying a J^2 "correction factor" (where J is available) compresses the horizontal spread between the curves, implying reliability uniformity within the industry. We note in closing this topic that the arrows of Fig. 7 represent lower limits to lifetimes of the gold units of Ref. 47. The inference that these units would be less reliable than their aluminum-metallized counterparts below temperatures of 150°C should be restrained until further test results become available.

F. Applications

Transistors offer good input-output isolation and are therefore much better suited to simple circulator-less amplifier uses than are two-terminal devices. At UHF in particular, bipolar units in Class C operation offer highest CW efficiency and power output of any single active device and can be broadbanded (octave bandwidths) without sacrificing power or efficiency. At higher frequencies, these devices offer proven reliability for near-term amplifier needs, but become less competitive from a power and efficiency view in comparison with FETs and IMPATTs. If linear operation is needed, Class A design can be utilized to obtain extremely low inter-modulation distortion (3rd order intercept $\sim$ 40-50 dBm) at reduced power

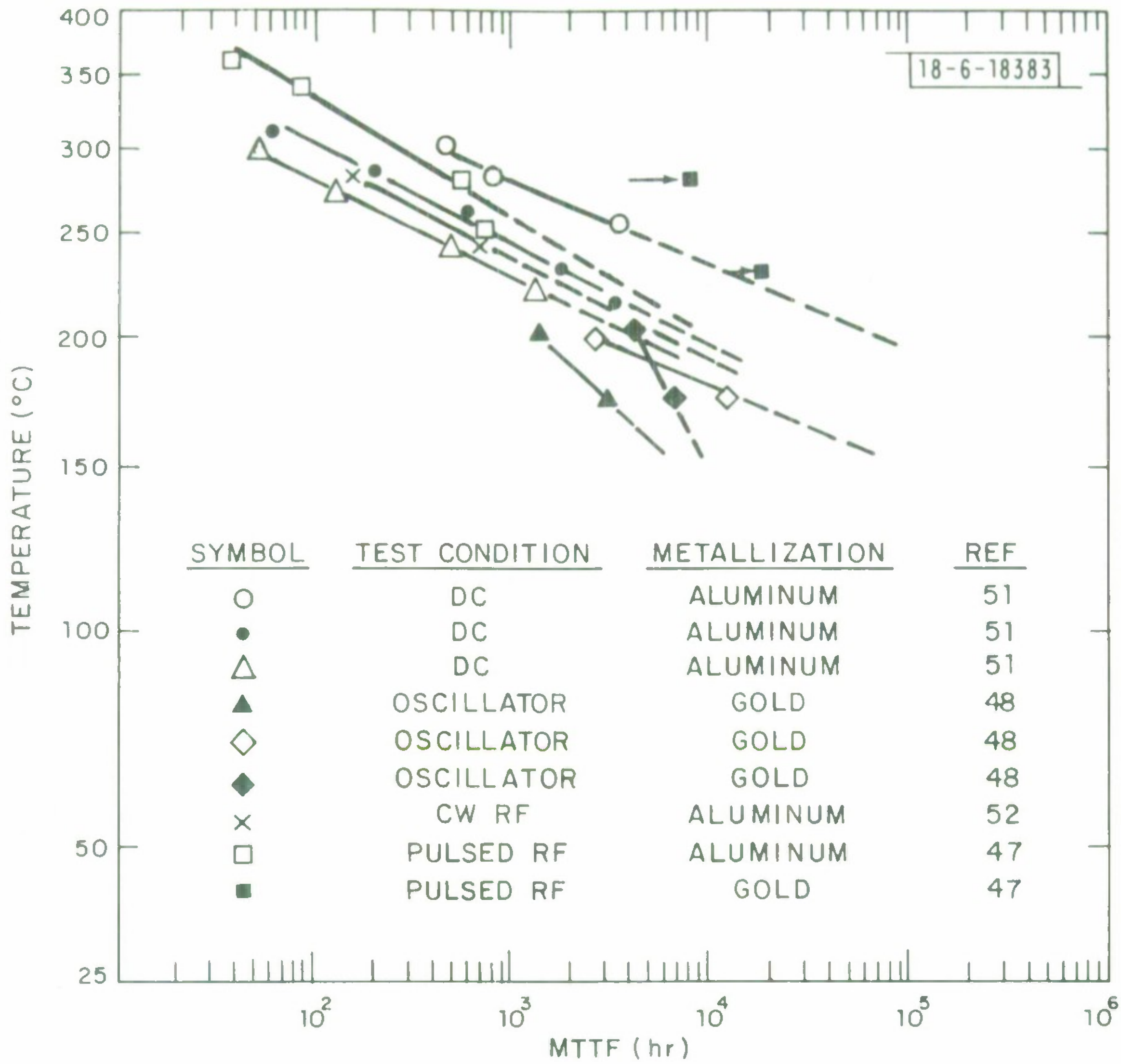

Fig.7. Bipolar transistor reliability results. Data points show median times-to-failure of populations of devices at specific junction temperatures. Straight lines represent a fit to an Arrhenius rate equation (see text). Dashed lines show extensions to lower operating temperatures. Test conditions, metallization schemes, and references are noted.

levels. In applications not directly related to this report, the bipolar has long been used for low noise applications and high power pulse work.

G. Future

Microwave bipolar power transistor development has been active at frequencies at and below 2 GHz. In this region, power output has doubled in the past 4 years[53]. These devices have demonstrated reliability as well as performance, and are commerically available at reasonable prices. Moreover, R & D efforts within the industry suggest that an additional doubling of power levels through 5 GHz is quite within reason within the next four years. A significant future development will be the development of dielectric isolation techniques allowing reduction in the number of wire bonds (currently on the order of 50 per device) in the finished package. The technology developed for lower frequency units is applicable to higher frequency devices, and some development work is underway[34], but the successes of FET power devices at frequencies above 4 GHz may divert bipolar funding from frequencies above this level. Silicon will continue to be the only material used for fabricating commercially available devices. GaAs bipolar devices have been fabricated, but are still in early stages of development.

IV. FIELD-EFFECT TRANSISTORS

Although conceptually older than the bipolar transistor, the field-effect transistor has only recently demonstrated its potential as a power amplifier in the microwave region. The microwave power FET is currently the most exciting solid state device; its success is due to the continuing advances in gallium arsenide technology, and its future promises further materials advances as well as geometric and circuit techniques to optimize performance. An in-depth review of these devices, including state-of-the-art results as of early 1976 has been published by Liechti[54]. As the bipolar transistor, the FET has no lower frequency limit of operation. Because its circuit parameters are relatively constant with both frequency and signal level, Class A (linear) operation with high efficiency and band-

width is realizable with straightforward circuit design procedures. Commericial units are available in the 10's of watts range through frequencies up to 1 GHz (these devices are silicon), but current development is concentrated on frequencies above 4 GHz, where bipolar power is extremely difficult to achieve. In this region, present FET added power capability is 4.8 watts at 4 GHz, 3.5 watts at 8 GHz, 1.2 watts at 12 GHz, and hundreds of milliwatts at 20 GHz. All these devices use GaAs material. Because the power FET is so new, device life and failure mechanisms are presently not well defined.

A. Device Description

A field-effect transistor consists of three regions: source, gate, and drain. Transistor action of this device is the control of majority carrier flow through the channel region between the source and drain terminals. The fact that the FET is truly a unipolar device means much fewer constraints are imposed on material selection and device fabrication is simpler than with bipolar devices. Voltage applied to the gate terminal modulates the conductance of the channel by depleting or enhancing a portion of the channel thus providing control of carrier flow. The gate electrode may be electrically isolated from the channel by a thin oxide layer (insulated gate FET or IGFET), it may be a diffused junction at the top of the channel (junction FET or JFET), or it may form a Schottky barrier contact to the channel (metal electrode-semiconductor FET or MESFET). All three types have application to power amplification at microwave frequencies but this discussion will concentrate on the GaAs power MESFET. Figure 8 shows a sectional view of this device with representative dimensions and doping levels. The inclusion of a buffer layer between the substrate and the epitaxial layer generally results in higher quality devices.

In general, the physics of the field-effect transistor is quite simple. Carrier motion is by majority carrier drift, a faster process than minority carrier diffusion, the process which determines current in bipolar transistors. Frequency response depends on the transit time of charge carriers beneath the gate contact. Device design procedure for the FET has not

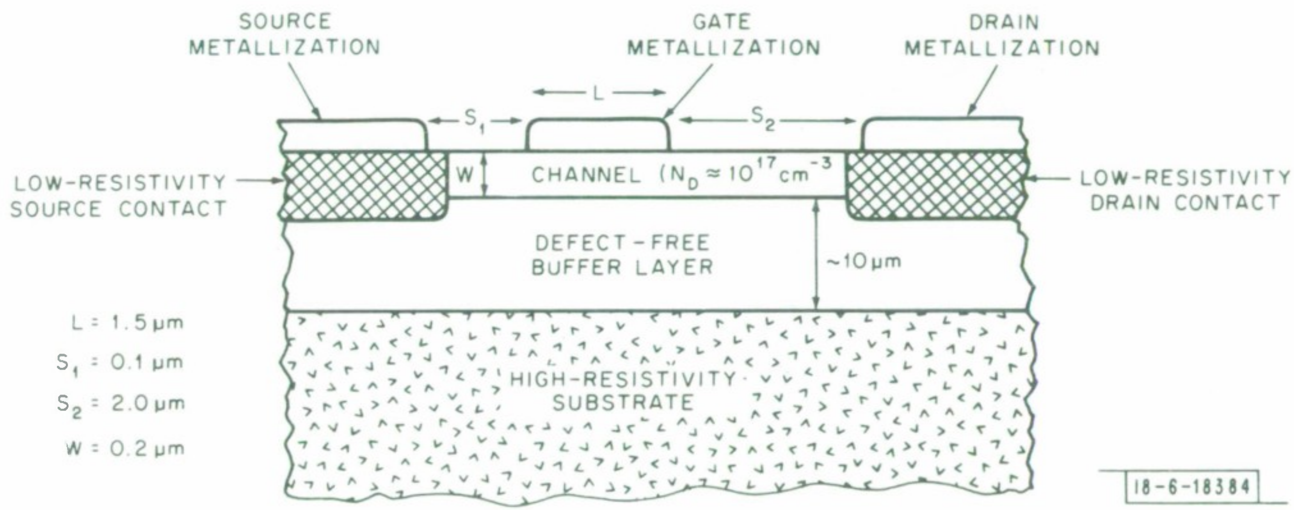

Fig.8. Device structure (cross-sectional view) of single-gate GaAs (n-channel) MESFET. Dimensions and doping densities are typical of a device designed for X-band operation. A "cell" is the array of repeated patterns of this structure, usually in interdigital fashion. Paralleling of cells is necessary for power devices.

reached the level of sophistication attained by bipolar devices, in some cases, because it is not needed. Because FETs are self-ballasting, for example, the bipolar-equivalent of emitter finger resistors are not required to insure current sharing in multi-channel cells.

Power handling capability depends on the gate periphery or "width", which determines the total dc current of the device. Other important parameters are the channel conductance and the breakdown voltage. Single gate width limits are set by series resistance of the finger metallization. Transmission line effects between gate and source fingers have also been proposed as a mechanism limiting the width of a single gate[55]. Multiple-channel "cells" are combined by direct wire bonding to construct a power device. Total gate width limits are set by eventual decreases in all RF power per unit added gate width, for reasons which are not fully understood. The decrease in impedance level caused by increased gate width is probably an important factor. Lateral non-uniformities in the grown layer of GaAs also hinder attempts to power combine.

B. Circuit Considerations

Small signal models of field effect transistors which are based on device physics and adequately characterize circuit operation have been developed for small signal optimization purposes. As for the bipolar transistor, f_T and f_{max} exist for FETs. The unity current gain frequency f_T describes the time required for the gate current to supply charge needed by a change in gate voltage. The relation between f_T and f_{max} is involved[56] but depends on the charging time constant of the gate and the input-output resistance ratio. It is worth noting that for a 1 μm gate device it is fairly easy to achieve $f_{max} \approx 50$ GHz. The input impedance is dominated by the depletion layer capacitance C_{gs} in the channel between gate and source. The portion of this layer between gate and drain accounts for the capacitance C_{gd} and determines stability and frequency response of the device.

Because the circuit elements of the FET are relatively constant as a function of signal level, linear operation is attractive. Class A designs

requiring medium- to high-power low distortion operation have been used at frequencies up to 20 GHz[57, 58]. Overdrive conditions used to increase large signal efficiency have been reported for FETs[59] just as they had for bipolars nearly ten years previous[60].

Straightforward power-combining techniques, from simple wire combining at the cell level* for best power and gain, to quadrature techniques for low VSWR[61], have recently been applied to FET power amplification stages. Reactive gain flattening at the input[62] is a simple broadbanding technique, which together with combining techniques and output circuit design to optimize saturated output power and drain efficiency, can be used to design broadband, linear, efficient power amplifiers[63]. Large-signal characterization of the output equivalent circuitry is appropriate when designing power stages, which can be as simple as interpreting the DC drain characteristics[62] to a detailed load-pull procedure[64].

C. RF Performance - 1977

Figure 9 shows the current performance of FET devices (CW added power vs. frequency) with power added efficiency and references noted. For a comparison with bipolar devices, see Figs. 6 and 12.

D. Reliability

No information regarding microwave power FET reliability is presently available. Various tests have isolated three distinct problems in achieving reliable operation of GaAs MESFETs in small signal applications:

1. gate diode burn-out
2. contact resistance degradation and contact metallization electromigration
3. temporal drift of dc and rf parameters.

Because of the inherently high input impedance of MESFETs, catastrophic burn-out failures can result from handling procedures and circuit environments which are not strictly

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* Execution of this technique is simpler with FETs (because of their higher impedance levels) than with bipolars.

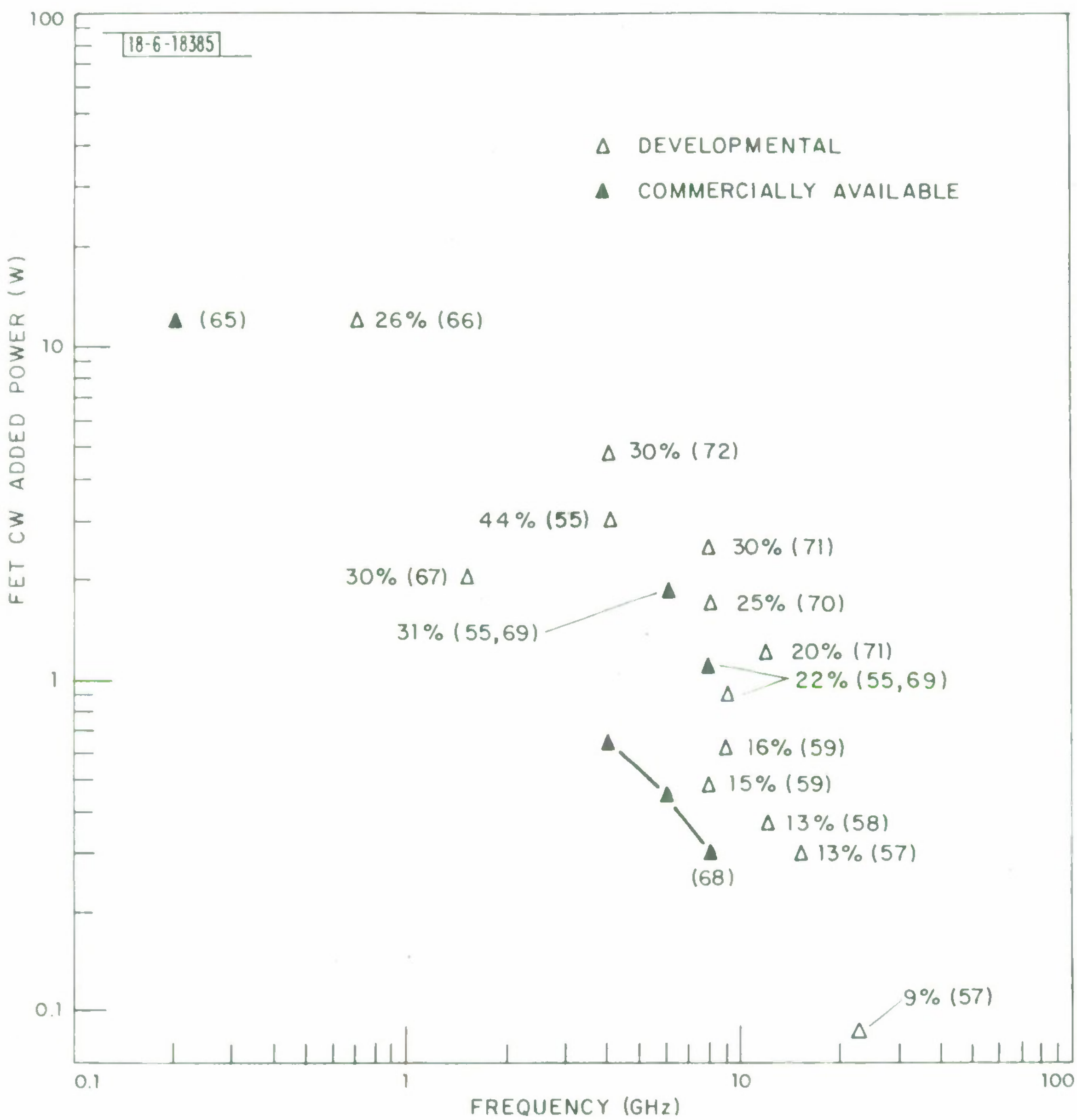

Fig.9. FET performance (CW amplifier added power vs frequency). Data points represent laboratory results or commercially available devices. Power added efficiency and references are noted for each point.

defined and regulated. These problems are similar to those encountered by manufacturers and users of mixer diodes. Abbott and Turner[73] describe tests showing the applicability of refractory metals for the Schottky barrier gate electrode. Careful handling procedures are still necessary to prevent accidental destructive breakdown.

High temperature and current density tests have determined source and drain contact degradation to be the cause of eventual (irreversible) device failure in small signal devices. Abbott and Turner[73] have noted electromigration effects in the contact metallization and have investigated several metallization schemes and device geometries in order to minimize the effect. Data for this failure mechanism is available, but in many cases preliminary, making quantitative lifetime estimates difficult.

(Reversible) degradation or instability of small signal parameters and RF gain has been a much-discussed reliability topic in low-noise FETs. A popular explanation is interfacial defect sites diffusing from the semi-insulating substrate into the higher-doped epitaxial layer[74]. Some vendors claim that the instability problem never existed with their device, or existed but was cured by proper treatment. The treatments include but are not limited to use of buffer layers as shown in Fig. 8.

E. Applications

The microwave power FET has established itself as a potential power amplification device at frequencies above 3 GHz in only the few years of its existence. Single-gate designs with large gate periphery ($\sim$ 1 cm) have been fabricated which show high power added efficiency together with high saturated added power with moderate gain. These devices might serve as output stages for multi-watt power amplifiers at X-band frequencies. Smaller periphery devices, including dual-gate designs offering higher gain, are good candidates for driver stages for such a system. The challenge to TWTs is clear. Linearity and noise performance intrinsic to FETs has been demonstrated. Recently, a single stage 4 GHz 300 mW amplifier with 13 dB gain and 40 dB carrier to interference ratio has been fabricated[75].

Also, a 3 dB noise figure with an associated gain of 10 dB at 8 GHz for a packaged device at room temperature is now commercially available[68]. The versatility of GaAs technology allows hybrid and even monolithic integration of these and other GaAs-based devices into compact, reliable, efficient subsystems. Such work is in progress.

F. Future

Although the microwave Power FET has made rapid advances in power at frequencies at and above 4 GHz in the last three years, it is still basically a laboratory device (as can be seen from representative price tags which are in the $1/mW range). The potential for inexpensive high yield processing exists already, [82] and pricing should be no real problem to power FET development. Its acceptance as a viable power alternative to bipolars and TWTs hinges on a demonstration of operational reliability, work that is in progress. Reliability aside, the future for the FET looks promising.

Some insight into the advances made in output power capability of FETs is provided by Fig. 10, which shows yearly developments in single device added CW power at X-band. Also shown is the added power per millimeter of gate width, which appears to be rising at the same rate. The message in this is that although gate periphery is being increased in order to raise power output, device fabricators are already investigating methods of improving performance at the single-cell level. Such efforts are well-spent because gate periphery of the larger devices is already producing input impedances of the order of 1Ω. This restriction may lead to real difficulty in producing single devices at X-band capable of more than 5 or 6 W.

Internal matching techniques and device geometry changes for thermal optimization, not fully exploited so far, should advance power capability to the same extent as they have for the bipolar transistor. New materials, such as InAs-GaAs[77] can be used for extending the frequency of operation, and new vertical technologies, such as the V-groove process, may allow simpler higher yield processing.

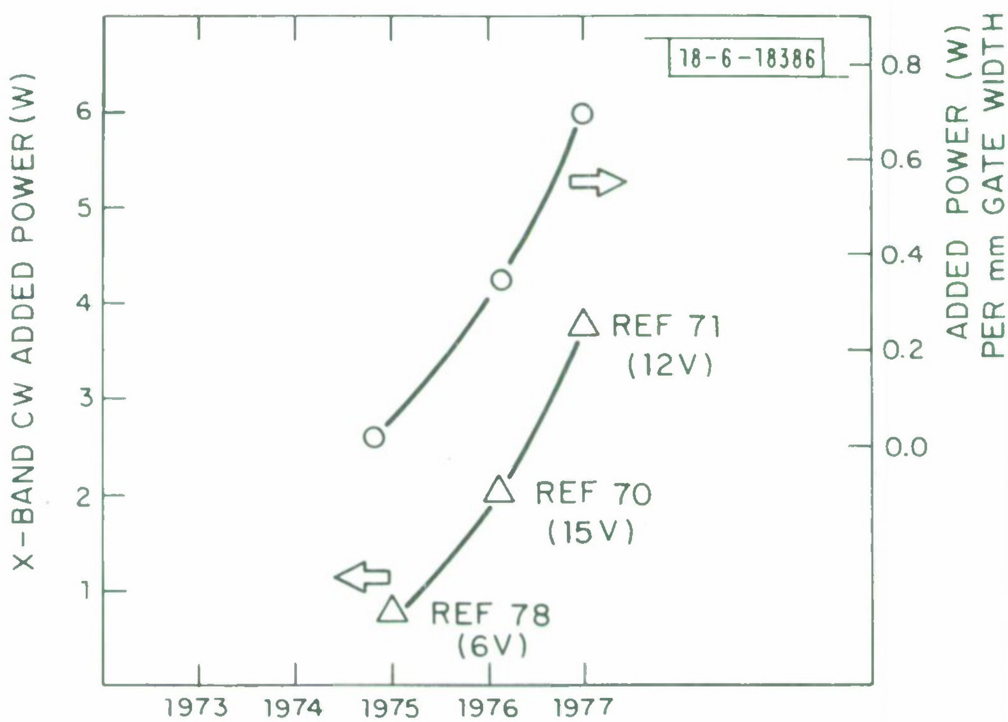

Fig.10. Recent yearly progress in FET power capability at X-Band. Total CW added power is compared with added power per millimeter of gate width as an indication of device design efforts. References and operating voltages are noted.

V. OTHER DEVICES

At least two other solid state devices exist which are capable of generating or amplifying power at microwave frequencies. We discuss briefly in the following transferred electron diodes and TRAPATT diodes.

A. TRAPATT Diodes

The TRAPATT (Trapped-Plasma-Avalanche-Triggered-Transit) diode has a structure almost identical to the IMPATT. The difference in operation, simply defined, is that whereas the avalanche region in the IMPATT is stationary, in the TRAPATT it moves, creating a dense plasma. TRAPATT performance, in contrast to IMPATT operation, is characterized by

1. higher current densities
2. lower frequencies of operation
3. higher efficiency
4. roughly equivalent noise performance

CW operation has been reported in the range from 0.5 — 10 GHz, but in this mode, in spite of its good efficiency, the TRAPATT has been shunned because among other things, out-of-band stability problems. Recently, Fong, et al.[79] have reported fixed-tuned pulse operation of TRAPATTs which suggest that a circuit environment allowing neither low frequency bias circuit oscillations nor high frequency harmonic power robbing is possible. Nevertheless, the development of modified profile IMPATTs, with comparable efficiency and power, and lower current densities, poses a stiff challenge to TRAPATTs for CW operation.

It should be mentioned that the TRAPATT in the pulsed mode offers the highest Pf^2 oscillator product of all solid state devices in the frequency region 1 — 100 GHz, and in contrast to modified profile IMPATTs, is fairly insensitive to temperature variations in pulsed operation. Efficiencies of operation as high as 60% have been observed in pulsed operation. Both device and circuit developments are continuing this area.

B. Transferred Electron Diodes

The family of transferred electron (TE) diodes exhibits features which recommend it to users interested in applications other than high efficiency CW power stages, and will therefore be discussed only briefly. There are three well-understood modes of operation in GaAs TE diodes: transit time, quenched domain, and limited space charge (LSA) operation. These devices are much less noisy than IMPATTs and as oscillators are used in both cavity-stabilized and voltage-tunable modes from 5 GHz to greater than 100 GHz. YIG-tuned units are finding increasing use as extremely stable sources, whereas varactor tuning is used where tuning speed is desired. Both are easily phase-locked to low-frequency standards. Although low-noise FET oscillators may challenge TE oscillators in noise performance in the future, the region above 10 GHz is presently the private property of the Gunn (transit-time) diode oscillator. Unfortunately, TE devices in the CW mode do not have powers and efficiencies which qualify them seriously for microwave power applications. Figure 11 shows CW-TE and TRAPATT oscillator performance with IMPATTs as a reference performance level. Where low noise high power amplification is desired, Gunn amplifiers in preamplification stages have been used with IMPATT power amplifiers[80].

VI. CONCLUSIONS

Figure 12 shows a composite power frequency plot of solid state (CW) power device performance in the microwave region. Bipolar devices shown here represent primarily those units which are commercially available with proven reliability. The associated technology is mature, and although the frequency of significant power applications seems limited to frequencies less than X-band, power increases for devices in this range are still predicted. IMPATT diodes are presently advancing their performance by using double-drift and modified profile techniques and improved heat sinking. A greater proportion of results at the upper power/frequency levels is R & D effort not presently commercially available or backed by demonstrated reliability. Finally, new FET results almost on a monthly basis, demonstrate the R & D activity level

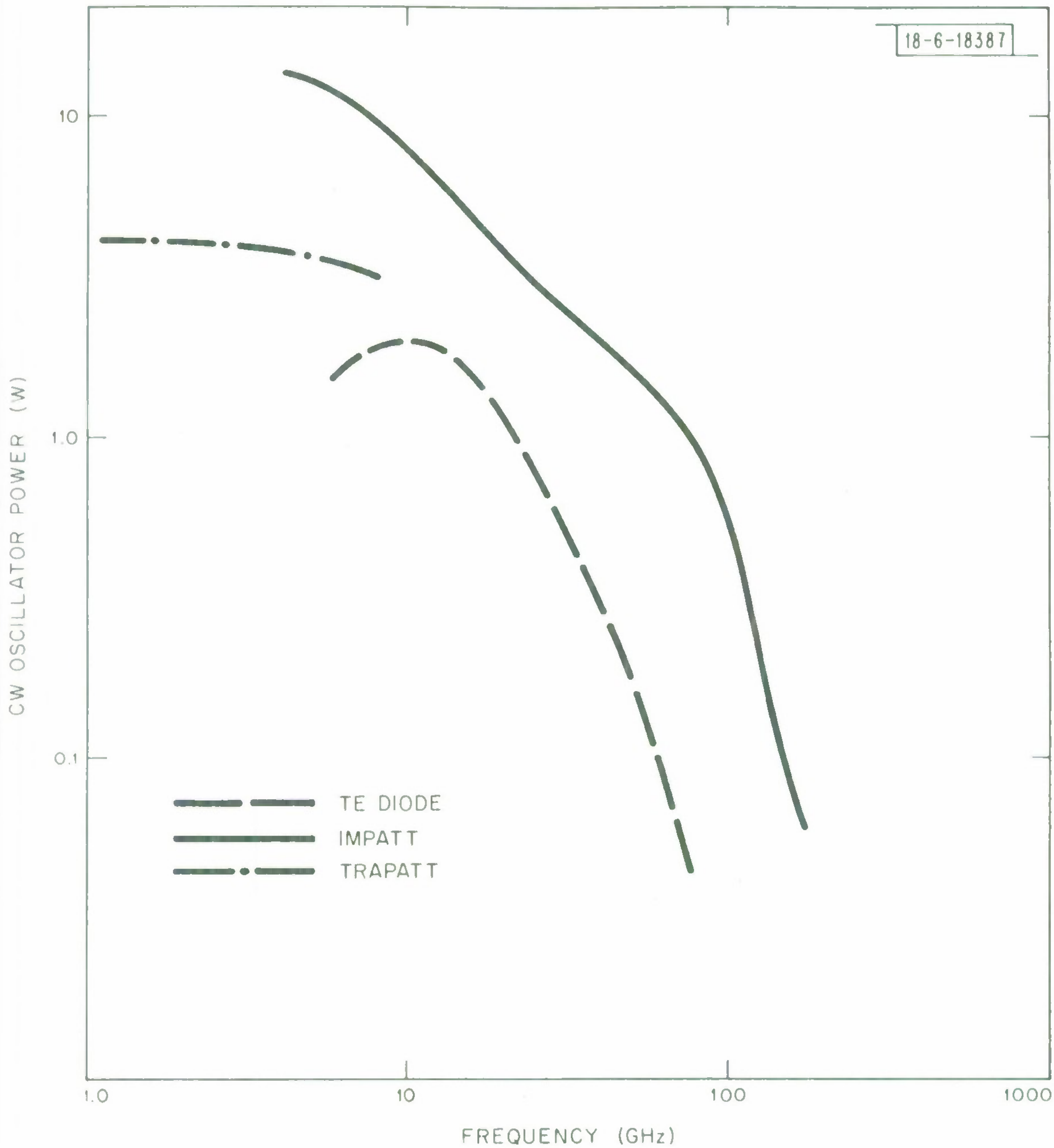

Fig.11. CW capability (output power vs frequency) of TE diodes and TRAPATTs compared to IMPATT results.

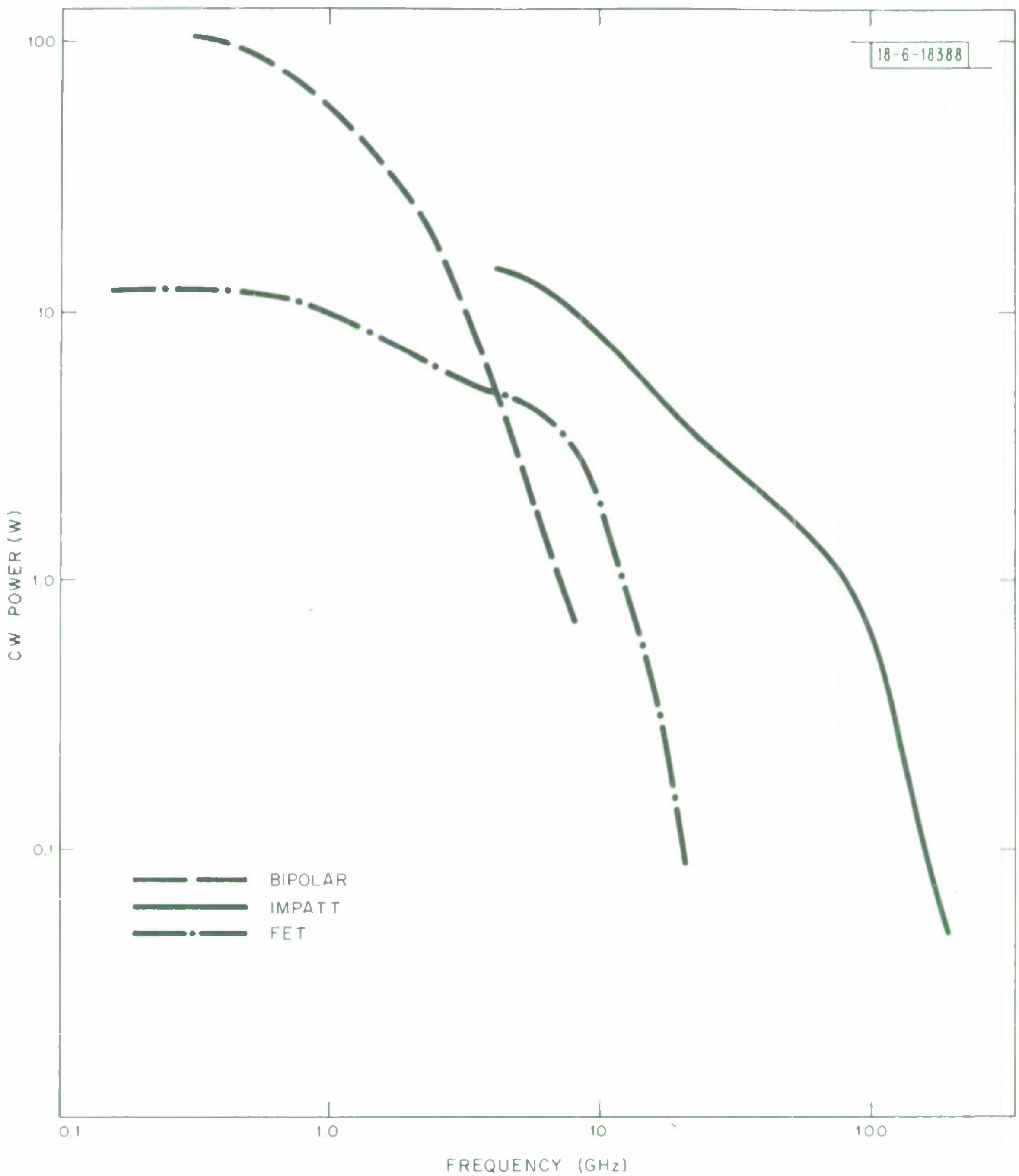

Fig.12. Summary of CW power capability of IMPATT diodes, bipolar, and field effect transistors (CW oscillator output power or CW amplifier added power vs frequency).

within this area. This device, although still in its infancy, is maturing rapidly because it is able to draw on many circuit and packaging techniques established for bipolar units.

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GLOSSARY

CTC	Communications Transistor Corporation, San Carlos, CA 94070
DDR	double-drift region
FET	field-effect transistor
HP	Hewlett-Packard, Palo Alto, CA 94304
IGFET	insulated gate FET
IMPATT	impact (ionization) avalanche transit time
JFET	junction FET
MESFET	metal-electrode semiconductor FET
MSC	Microwave Semiconductor Corp., Somerset, NJ 08873
MTTF	median-time-to-failure
NEC	Nippon Electric Company, Ltd; Kawasaki, Japan
PHI	Power Hybrids, Inc., Torrance, CA 90501
SDR	single-drift region
TED	transferred electron diode
TI	Texas Instruments, Inc., Dallas, TX 75222
TRAPATT	trapped plasma avalanche-triggered transit
TRW	TRW, Inc., various locations
TWT	travelling-wave tube

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Current capabilities of solid-state microwave power devices useful for CW power amplification in satellite communication systems are described. Devices discussed in detail include IMPATT diodes, bipolar and field-effect transistors. Also discussed are transferred electron diodes and TRAPATT diodes. Topics considered include physical device description, circuit design and performance, reliability, applications, and future trends.

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